N88-11143

DEVELOPMENT OF HEAT FLUX SENSORS FOR TURBINE AIRFOILS [†]

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INTRODUCTION

The objectives of this program are to develop heat flux sensors suitable for installation in hot section airfoils of advanced aircraft turbine engines and to experimentally verify the operation of these heat flux sensors in a cylinder in cross flow experiment. During the first phase of the program, embedded thermocouple and Gardon gauge sensors were developed and fabricated into both blades and vanes. They were then calibrated using a quartz lamp bank heat source and finally subjected to thermal cycle and thermal soak testing. This work has been reported in Reference 1. In the second phase of the program, these sensors were fabricated into cylindrical test pieces and tested in a burner exhaust to verify the heat flux measurements produced by these sensors. This paper describes the results of the cylinder in cross flow tests and reviews the conclusions and recommendations resulting from the test program.

DESCRIPTION OF THE TEST PIECES

Two test pieces were fabricated from Hastelloy-X tubing 1.6 cm. in diameter with a wall thickness of 0.15 cm. An embedded thermocouple sensor, a Gardon gauge sensor and a slug calorimeter were fabricated into each test piece spaced 5 cm. apart. Figure 1 shows the sensor locations in one of the cylinders. Design details of the test pieces and fabrication of the sensors are given in References 2 and 3. Steady state heat flux measurements were made with the embedded thermocouple and Gardon gauge sensors and transient heat flux measurements with the Gardon gauge sensor and slug calorimeter. These sensors were calibrated using a quartz lamp bank as a heat source and a commercially available heat flux sensor as a transfer standard. Two other test pieces, fabricated from 1.6 cm. diameter NiCoCrAlY tubes having a wall thickness of 0.48 centimeters, were instrumented with an array of sputtered thermocouples to measure the fluctuating metal surface temperature. This information, in conjunction with fluctuating gas temperature measurements made with the dynamic temperature probe developed under contract NAS3-23154 (Ref.4), was to be used to calculate the heat transfer coefficient.

DESCRIPTION OF THE TEST PROGRAM

Tests were run in the exhaust of a Becon type atmospheric pressure combustor with a 5 cm. diameter exhaust nozzle. The cylinders were positioned downstream of the nozzle and mounted on a traverse can capable of both linear and rotational movement. Prior to running the tests with the cylinders, a series of tests was conducted to characterize the exit gas temperature and pressure profiles from the burner, using an aspirating thermocouple probe and a pressure probe. Data were obtained at temperatures from 1500 to 1760K and Mach numbers from .42 to .74. The aspirating thermocouple probe was used throughout the test program to set the burner

† NASA Contract NAS3-23529

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conditions. The test setup is shown in Figure 2. For the steady state points, the burner conditions were stabilized and the internally cooled cylinder was traversed into position in the gas stream to make the measurements. The transient tests were run with the uncooled cylinder initially out of the gas stream to maintain a uniform temperature and then shuttled rapidly into the gas stream to start the transient.

TEST RESULTS

Figures 3 and 4 show typical pressure and temperature profiles in the combustor exit. Based on the profile data generated in these tests, as well as laser doppler velocimetry (LDV) data obtained on a similar combustor at NASA Lewis, the primary location for data acquisition was selected at a distance of 5 cm. behind the nozzle. Data from the steady state sensors on both cylinders at the stagnation point plotted as a function of Mach number is shown in fig. 5. The data from the two embedded thermocouple sensors show reasonable agreement, while the data from the two Gardon gauge sensors show a wide variation which is believed to be due to the placement of the junctions internal to the Gardon gauges. To confirm this, the cylinders were rotated to acquire data around the circumference of the cylinder. Figure 6 shows the variation in heat transfer coefficient around the cylinder measured with the two embedded thermocouple sensors. These match the profiles widely reported in the literature. Figure 7 shows similar data as acquired from the two Gardon gauge sensors. These data seem to indicate that the two sensors were built with the junctions located off the stagnation point in opposite directions, and that the circumferential temperature gradients in the cylinders may be causing significant differences in the outputs. A finite difference thermal analysis was run, which confirmed that the observed output can be predicted based on the location of the thermocouple junctions. The data from the transient sensors at the stagnation point plotted as a function of Mach number are shown in fig. 8. This data is well behaved and indicate an increase in the heat transfer coefficient as the Mach number is increased.

Figure 9 shows a plot of the ratio of the measured heat transfer coefficient to the calculated heat transfer coefficient plotted against Mach number for both the transient and steady state sensors. The calculated heat transfer coefficient is based on zero turbulence. The NASA LDV data indicates a turbulence level of about 10% could be expected, hence, the ratio should be significantly greater than 1. The transient sensors yield a ratio that is about 10% greater, while the steady state sensors generally yield a ratio that is up to 70% greater than 1. This difference is consistent between sensors and between runs and is currently unexplained.

All the sensors were operational at the end of the test program. A recalibration of the sensors was performed which revealed the sensors outputs were within 3% of the pretest values, indicating there were no shifts in output or degradation of the sensors during the test program.

The test program on the cylinders with sputtered thermocouples yielded heat transfer coefficients that were an order of magnitude higher than those measured with the other cylinders. Inspection of the data revealed that the dynamic temperature probe performed properly and that the temperature fluctuations measured with the sputtered thermocouples were unrealistically high. A post-test examination of the cylinders revealed that the sputtered thermocouples developed shorts to ground as the cylinder temperature was raised. The sputtered thermocouples also exhibited adherence problems and most of the films had lifted by the end of the test. The unrealistically high ouput from the sputtered thermocouples is believed to be due to ground loops, ion effects from the flame, or undesired thermoelectric effects from the NICoCrAlY. It is planned to install new sputtered thermocouples on the cylinders and rerun tests to obtain valid data.

CONCLUSIONS AND RECOMMENDATIONS

In general, the steady state sensors produced heat transfer coefficient measurements that were up to 70% higher than theoretical predictions for zero turbulence. This would be anticipated from the approximately 10% turbulence reported from the LDV results. There is a systematic bias between the steady state measurements and the transient measurements. The transient measurements produced heat transfer coefficients only up to 10% higher than the theoretical predictions for zero turbulence which are lower than would be anticipated with the 10% turbulence levels. All repeat points on the sensors were within 10% and some of this variation may be due to repositioning the cylinder in the gas stream. The post-test calibration values were within 3% of the pre-test values, indicating that the sensor outputs were stable and the environmental conditions did not cause shifts in the sensor outputs. The dynamic temperature probe gave good results throughout the test, but the durability and performance of the sputtered thermocouples was very poor.

The following recommendations are offered in light of the experience gained from this test program:

1. Use of sensors in hot section airfoils should be limited to areas that approximate flat plate geometries and where temperature gradients are minimal.

2. Use of embedded thermocouple sensors instead of Gardon gauge sensors should be favored in areas with moderate thermal gradients.

3. Develop methods of calibrating heat flux sensors in areas of sharp curvature and large temperature gradients.

4. Improve the durability of the sputtered thermocouples and conduct a test program to evaluate the use of sputtered sensors within a flame.

REFERENCES

1. Atkinson, W. H.; Cyr, M. A.; and Strange, R. R.: Turbine Blade and Vane Heat Flux Sensor Development. Phase 1 Final Report NASA CR-168297, August 1984.

2. Atkinson, W. H.; Cyr, M. A.; and Strange, R. R.: Turbine Blade and Vane Heat Flux Sensor Development. Phase 2 Final Report NASA CR-174995, 1985.

3. Atkinson, W. H.; and Strange, R. R.: Development of Heat Flux Sensors in Turbine Airfoils. NASA Conference Publication 2339, October 1984.

4. Elmore, D. L.; Robinson, W. W.; and Watkins, W. B.: Dynamic Gas Temperature Measurement System. Final Report NASA CR-168167, May 1983.

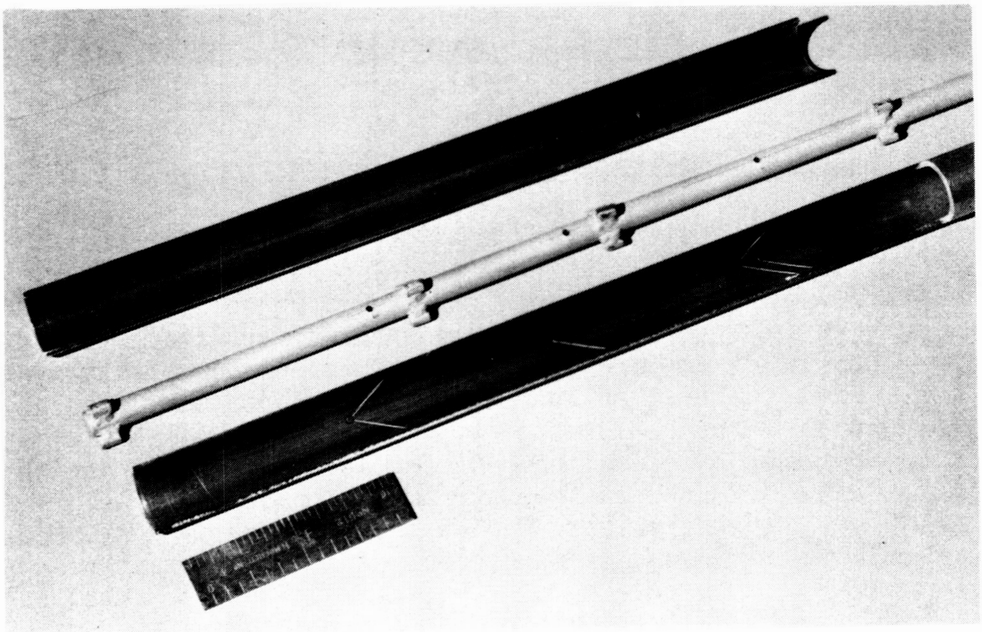

Figure 1 Test Piece During Fabrication Showing Sensor Locations

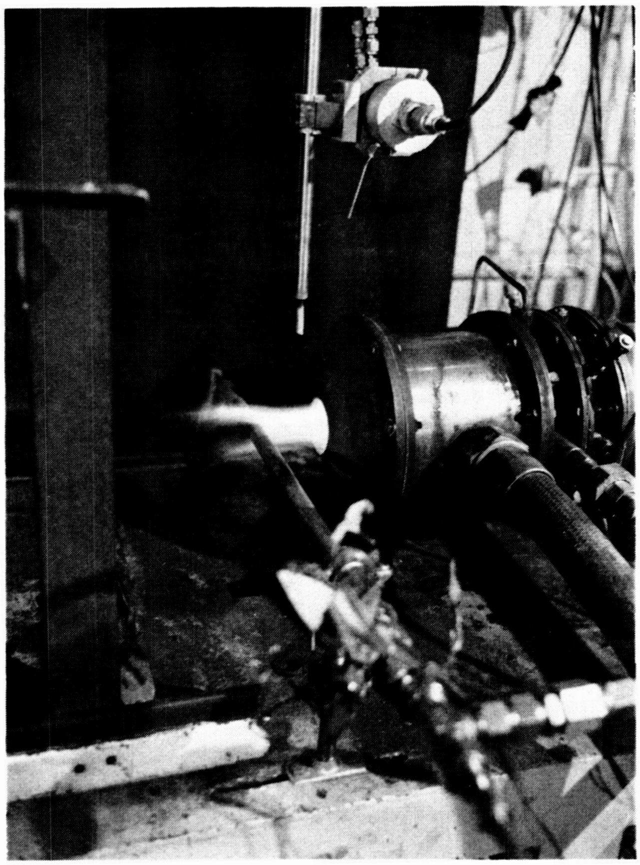

Figure 2 Cylinder in Cross Flow Test Setup

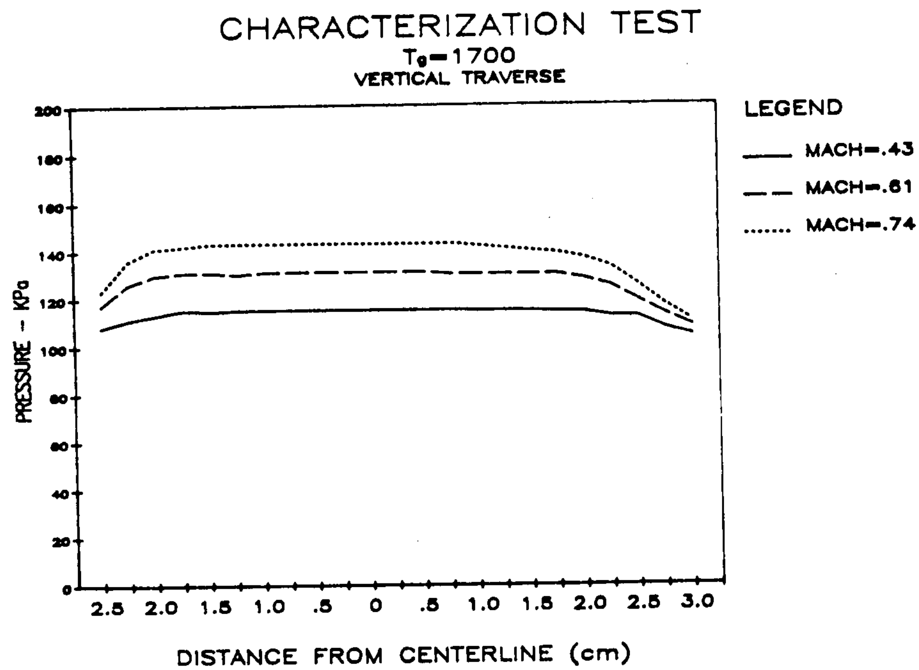

Figure 3 Pressure Profile Across the Burner Exhaust

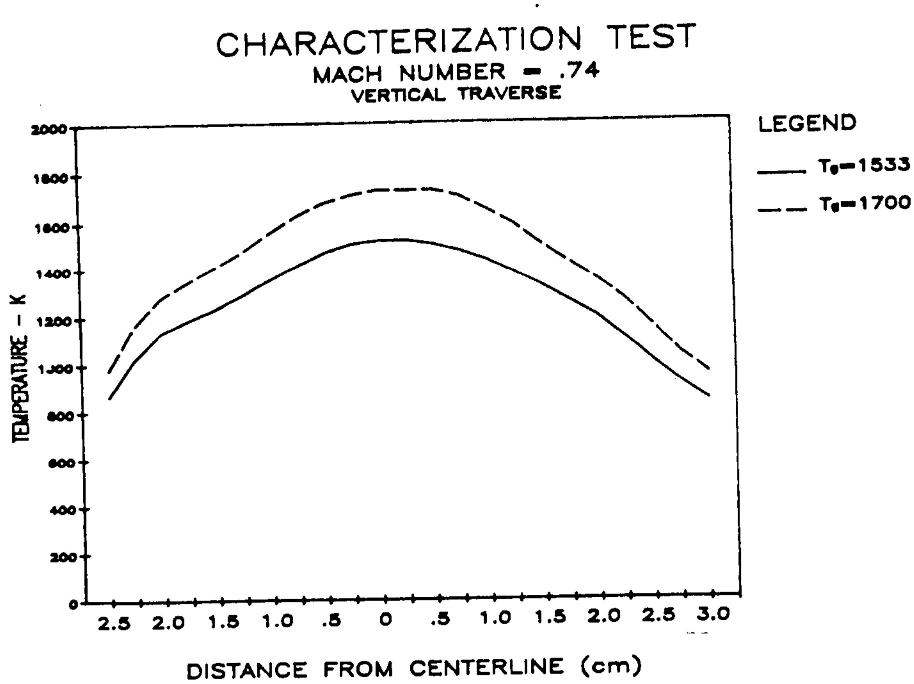

Figure 4 Temperature Profile Across the Burner Exhaust

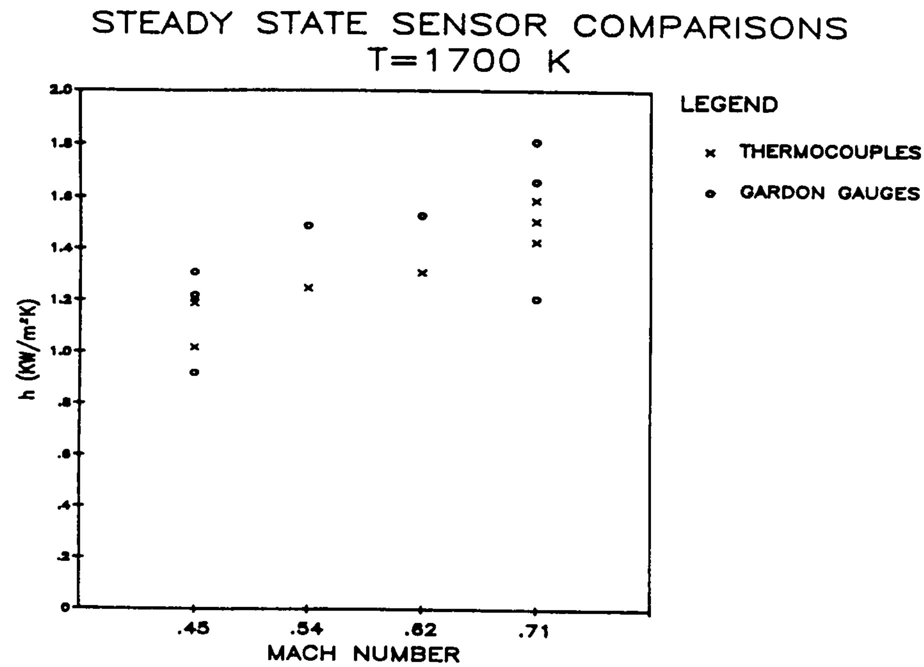

Figure 5 Steady State Heat Flux Sensor Data

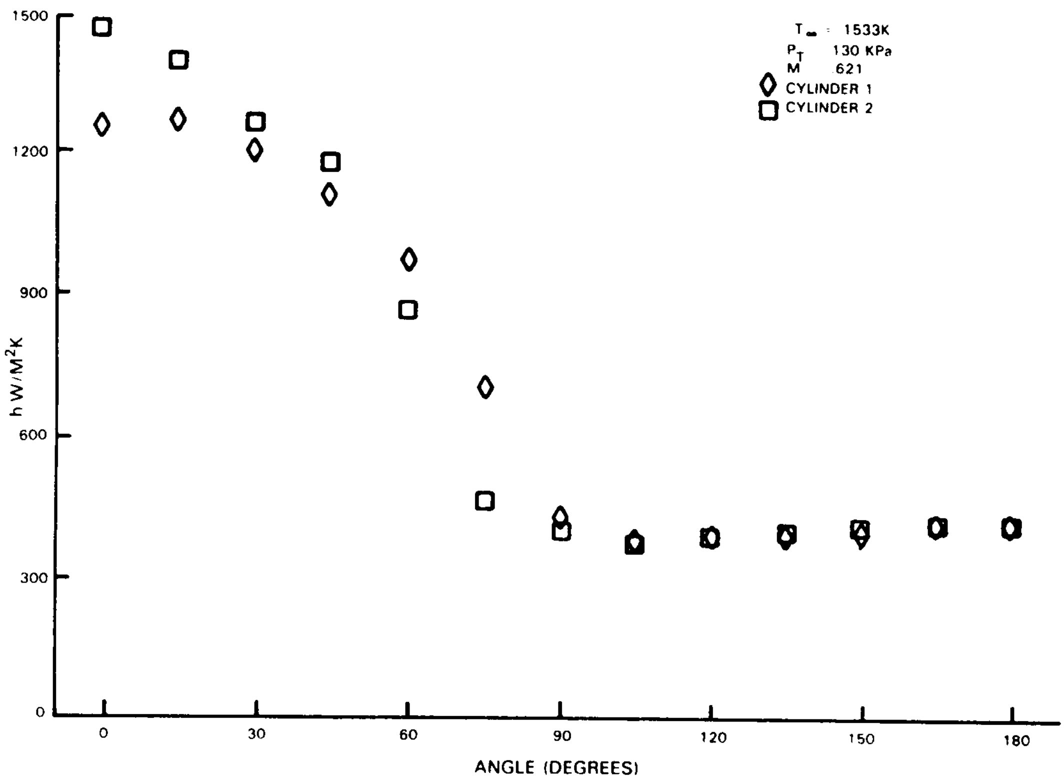

Figure 6 Heat Transfer Coefficient Variation Around the Cylinder As Measured with the Embedded Thermocouple Sensors

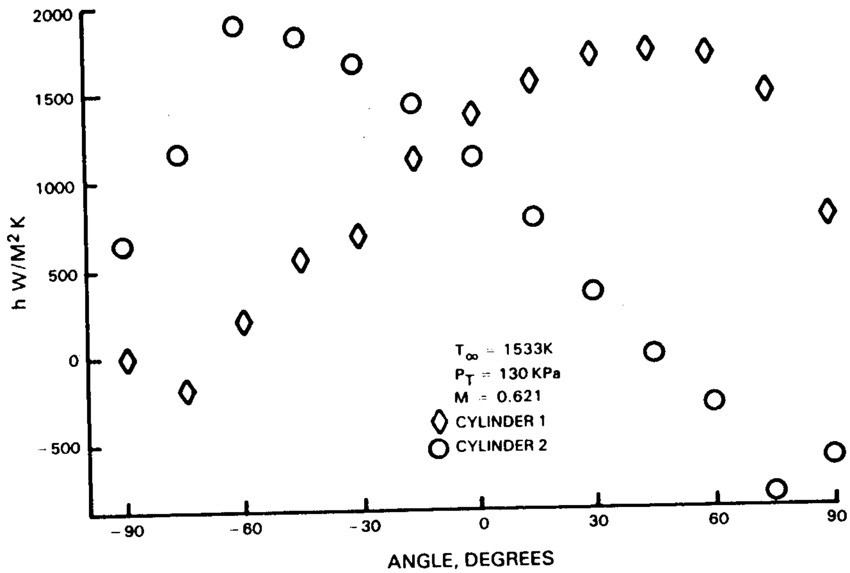

Figure 7 Heat Transfer Coefficient Variation Around the Cylinder As Measured with the Gardon Gauge Sensors

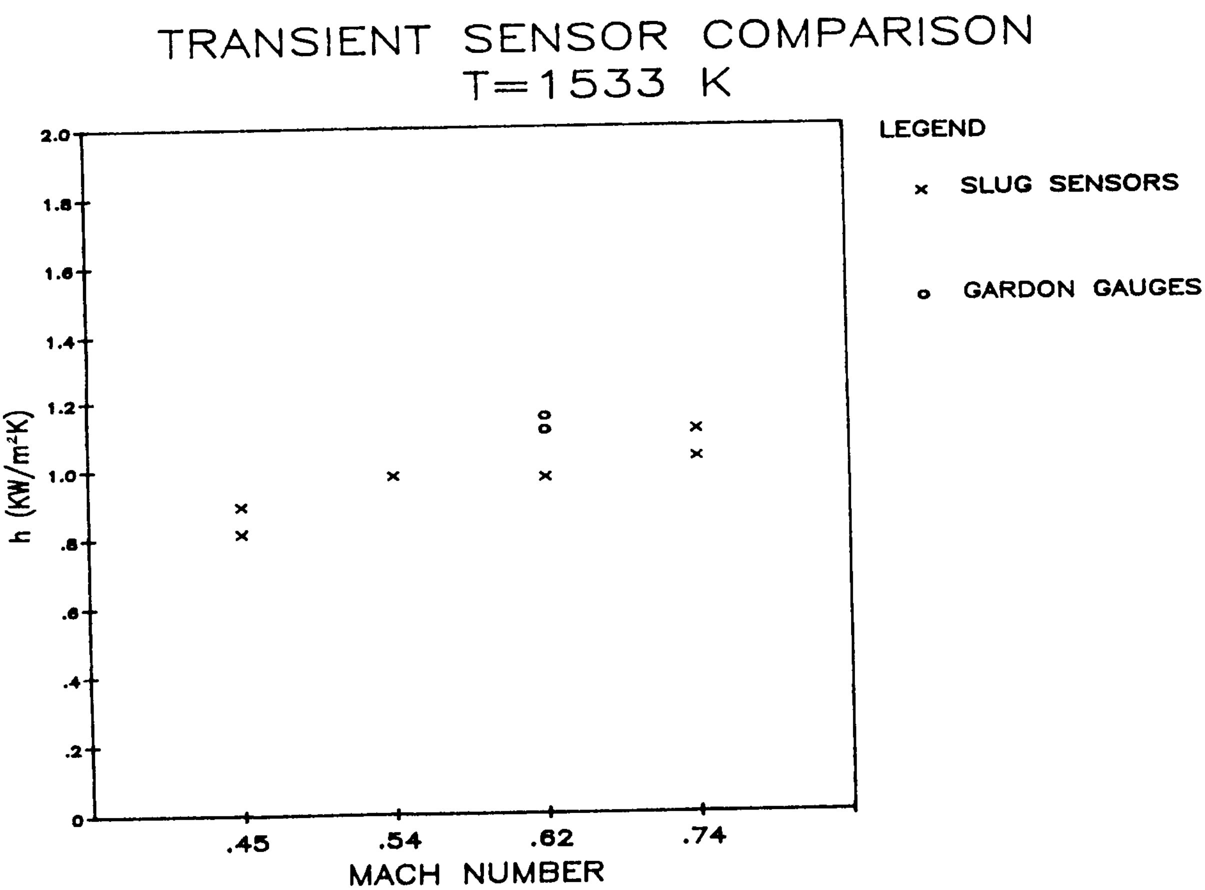

Figure 8 Transient Heat Flux Sensor Results

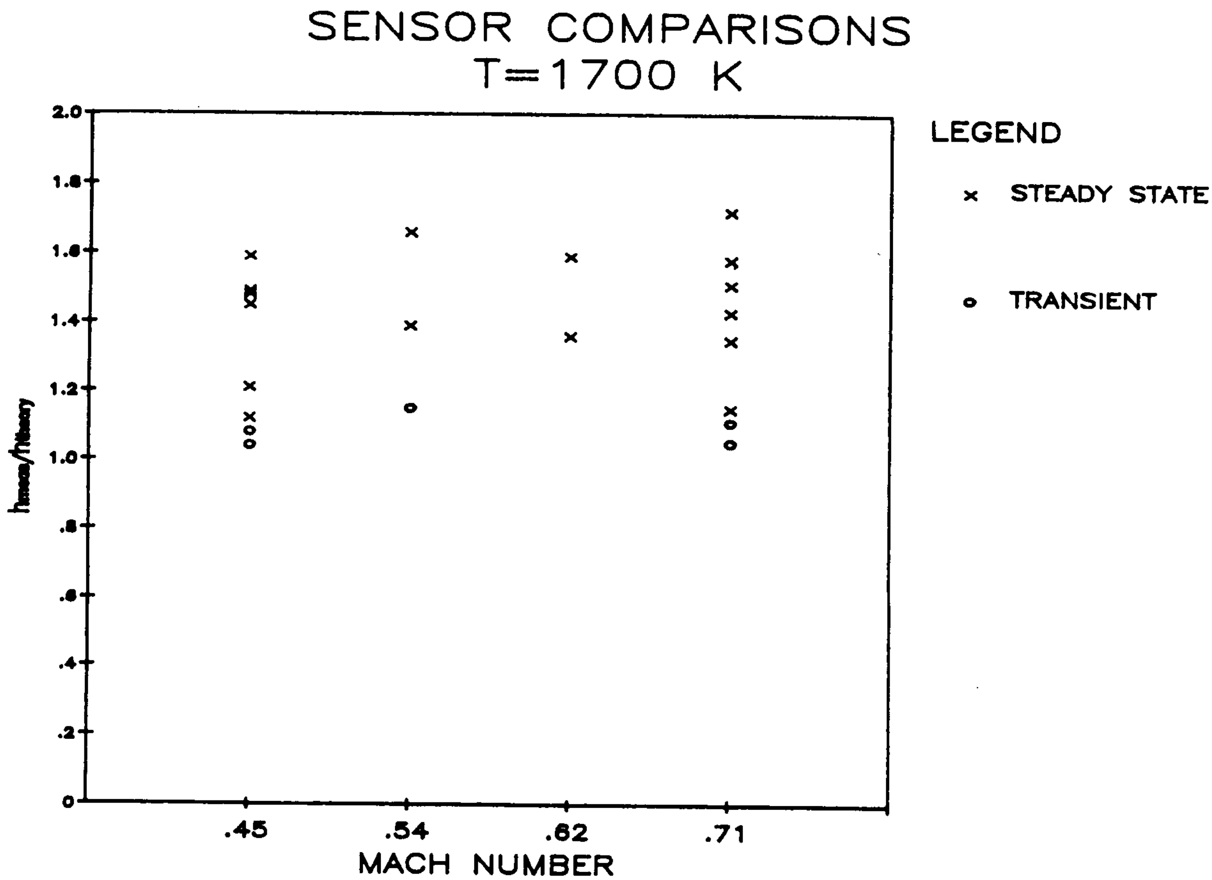

Figure 9 Comparison of Measured Heat Transfer Coefficients with Theoretical Predictions